A Tire Friction Characteristic and Braking Performance in High-Speed Driving

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ABSTRACT

The objective of pavement is to provide the good roughness and safe road surface efficiently to traffic. It needs safe and comfortable surface through the design speed of road. One of the pavement surface performances, Skid resistance is changed through driving speed. In high speed driving, there is dangerous not in the same class as proposed roads one.

Therefore in this study, we analyze speed equation about existing braking distance, propose the friction coefficient in high speed driving using the principle of the conservation of energy.

1 Introduction

Performances required for a car and a tire are very diverse such as handling performance, brake, durability, wear-resistance, NVH performance, fuel-efficiency performance, etc to name a few. Out of these performances required, car performances which are most closely related to the driver's stability are handling performance and brake performance. Recently, technology has been evolving towards greater stress on customer stability by installing ABS system and an air-bag, which are relevant to the driver's safety. Three elements determining performances of the ABS are the ABS system of the car, brake characteristic of the brake and friction characteristic of the brake pad. Much effort has been made to develop this technology.

The introduction of NCAP (New Car Assessment Program) into Korea in 2001 has formed an atmosphere or an environment which takes brake performance of the car seriously among local car manufacturers. Thus, automobile manufacturers' expectation about brake performances of the tire has risen steeply. Accordingly, this created external environment which spurs tire manufactures to develop technology improving performances of Abs braking. With regards to this aspect, this paper aims to introduce research results concerning brake performances of the tire. Currently, the limiting speed is restricted to 100km/h not only by NCAP tests but also under most of local road conditions. However, road conditions have been evolving to enable cars to run in high speed (100km/h or faster) compared to road conditions in the past thanks to improvements of car performances. As the most basic consideration to give while running in high speed is the driver's safety, forecast on brake performances of the car depending on speed change deems to be very significant.

Under the management of the Ministry of Land, Transport and Maritime Affairs, a verification and announcement system about collision durability and ABS braking performance of the car which are directly linked to the driver's life has been introduced in Korea recently with limitation to new cars for domestic consumption. While car collision tests have already been performed, a system which announces brake performance to consumers by assessing brake performances of new cars fitted with ABS under dry and wet condition was introduced in 2001 to protect consumer's interest. This system is referred to as New Car Assessment Program (abbreviated to NCAP) and has been implemented in advanced countries such as the USA or Japan.

2. Introduction of friction mechanism depending on road surface characteristics

According to the Coulomb Law, friction coefficient of perfectly elastic body such as steel is determined by load and friction force of the body and the value of friction coefficient can not exceed 1. However, an object such as elastomer becomes deformed when external force is applied. Thus, a mechanism of interpreting this process becomes far more complicated. More minutely, the mechanism needs to be interpreted in totally different way depending on the texture of road surface with which elastomer contacts.

As shown in the formula 1), the friction coefficient of the elastomer is determined by adhesion friction coefficient by molecular interaction between the road surface and elastomer, the hysteresis term by deformation of elastomer and the cohesion term by wear or tear.

$$\mu_{overall} = \mu_{Adhesion} + \mu_{Hysteresis} + \mu_{Cohesion} \quad (1)$$

Here, the adhesion means friction mechanism which occurs by polymer interaction between surfaces in other words between the tread rubber and the road surface and determines friction characteristics on the smooth and dry road surface as shown in Figure 2-3. Especially, this is the friction mechanism which determines grip on the icy or snowy road surface.

Figure 1) Friction-occurring mechanism scheme depending on texture of road surface

Hysteresis is a frictional characteristic by the loss of hysteretic energy which occurs due to repeated deformation of the tread. As the hysteresis acts as the major factor on the wet road surface, hysteresis characteristic of the compound is very important for wet brake performance. The friction coefficient by cohesion expressed in wear and tear is relevant to abrasion characteristic of the tread rubber and is significant for very rough road surface. However, the influence of the friction coefficient by cohesion on the total friction coefficient is as slight as negligible compared to adhesion or hysteresis term generally.

Below is the summary of grip characteristics depending on characteristics of the road surface. While a compound having superior adhesion feature is favorable to a smooth road surface, a compound having high hysteresis is favorable to a rough road surface and a compound having superior wear-resistance and high tear energy is advantageous to a sharpened road surface.

In case of snow or ice grip which is relevant to smooth road surface, softer compound is more advantageous to grip and accordingly, a compound with low hardness is used. Since rubber tends to be hardened as the temperature drops, grip of rubber is deteriorated on icy road surface. Thus, to prevent this, it is desirable to use silica compound having low temperature dependency against hardness.

The adhesion mechanism occurs by molecular interaction between rubber and the compound of road surface. The adhering element is the one which has higher adhesion on the dry road condition. When the road surface is wet, adhesion decreases generally. Therefore, friction loss occurs on the wet road.

The hysteresis mechanism expresses energy loss as deformation of rubber when rubber slides on the road compound. Table 1) summarizes friction mechanism depending on characteristics of road surface as mentioned above.

Table 1) Friction mechanism depending on characteristics of road surface

	Adhesion	Hysteresis	Cohesion
Mechanism	Molecular Interaction	Deformation	Wear & Tear
Road Surface	Smooth	Rough	Sharp
Comp’d factor	Soft	High Hysteresis	High Wear Res.

The result of measuring wet friction coefficient using Dynamic Friction Tester (DFT) on diverse types of road surface is described below. As shown in Figure 2), four types of road surface are prepared for this test in the laboratory. DFT is a device of measuring friction coefficient using a rotating disk plate.

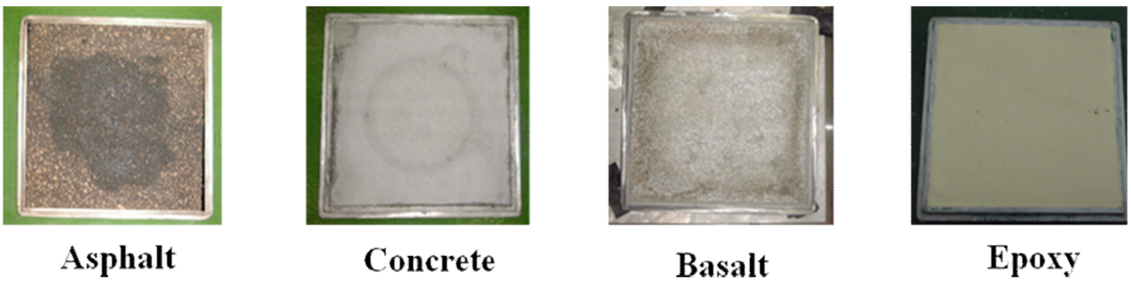

Figure 2) Road surface texture

To explain how the friction coefficient is measured by the DFT shown in Figure 3), the DFT measures friction force until the disk plates stops by friction between 3 rubber samples attached to the rotating disk plate and the road surface.

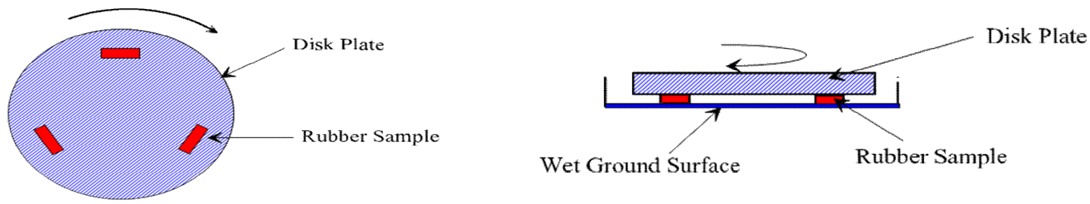

Figure 3) Operational principle of Dynamic Friction Tester

According to test results summarized in Table 2), wet friction coefficient for asphalt and concrete is 0.73 and 0.46 respectively, whereas wet friction coefficient for epoxy which is similar to icy road surface is less than 0.1.

Table 2) Result of friction coefficient depending on road surface texture

Surface (Wet)	Asphalt	Concrete	Basalt	Epoxy
Test Speed	80KPH	80KPH	80KPH	40KPH
Friction Coefficient	0.73	0.46	0.40	0.08

3. Influence of speed on braking distance or friction coefficient

3-1. Influence of speed on the friction coefficient

In general, traction performances of the tire are indicated as braking distance and the friction coefficient, which is expressed as μ-slip ratio curve. Firstly, how the friction coefficient changes depending on the change of speed will be addressed.

As shown in Figure 4), major characteristic values relevant to friction characteristic need to be understood.

Figure 4) Friction Coefficient and Slip Ratio Curve

Slip Ratio on the axis of abscissa is defined as speed ratio between the car and the wheel as indicated in Formula 2). Peak Friction Coefficient (μ_p) means the highest friction coefficient according to the change of slip ratio and Sliding Friction Coefficient (μ_s) means the friction coefficient when the wheel starts sliding as the wheel is locked.

Braking Stiffness means the gradient of friction coefficient on the initial slip ratio and is relevant to stiffness, foot length and foot width of the tire.

$$\textbf{Slip ratio} = \frac{V_{vehicle} - V_{wheel}}{V_{vehicle}} \times 100$$ Formula 2)

Friction tests were performed for 205/60R15 tire using the DFT with the focus on the change of friction characteristic depending on speed change.

Below Figure 5) shows dynamic friction behavior of the tire with the change of speed from 50Km/h to 110km/h.

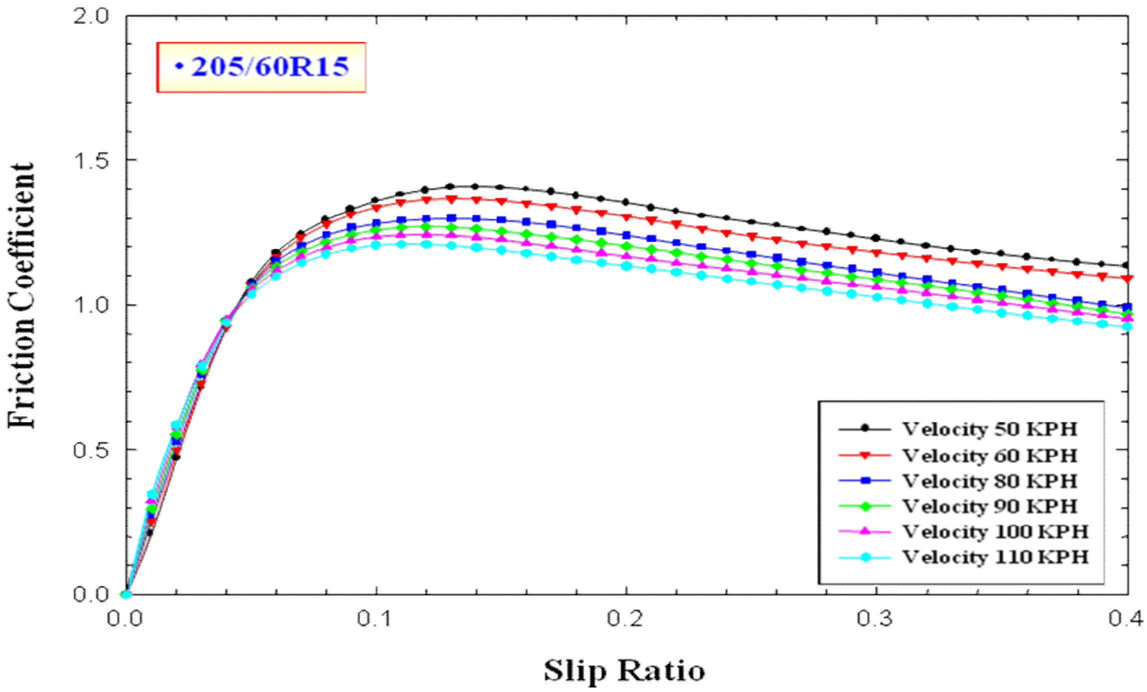

Figure 5) Friction characteristic depending on speed change

According to above Figure 5), Peak Friction Coefficient (μ_p) and Sliding Friction Coefficient (μ_s) decreases as the speed increases while a car brakes. The field of slip ratio where peak friction occurs also decreases.

4. Theoretical Background

Energy balance between Formula 3), kinematic energy of the car and Formula 4), friction energy between the road surface and the car is required to convert the braking distance of the car into friction coefficient.

In Formula 3), m and v means load and speed of the car respectively. In Formula 4), μ and L means friction coefficient and braking distance.

$$E_{kinetic} = mv^2/2$$ Formula 3)

$\mathbf{E_{friction} = \quad mgL}$ Formula 4)

$\mathbf{E_{kinetic} = E_{friction}}$

If it is possible to assume that the friction coefficient is constant irrespective of the speed, it can be expressed as Formula 5).

$\mathbf{L = v^2/(2g \quad)}$ Formula 5)

If the friction coefficient is the function of speed, considerations will be given to two cases – decrease of the friction coefficient in proportion to speed as show in Formula 6) and decrease of the friction coefficient in exponential function as indicated in Formula 7).

$\mu = \mu_o(1\text{-}Av)$ Formula 6)

$\mu = \mu_o exp(\text{-}Bv)$ Formula 7)

Here, $_o$ is Intrinsic Parameter which is irrelevant to the speed. *A and B* is constant.

If the friction coefficient is the function of speed, the braking distance can be expressed in Formula 8).

$$L = \int \frac{v}{\mu(v)g} dv$$ Formula 8)

Firstly, if the friction coefficient is linear function of speed, the brake distance is expressed in Formula 9) by substituting Formula 6) for Formula 8).

$$L = \int \frac{v}{\mu_o(1-Av)g} dv = \frac{1}{A\mu_o g}[\frac{1}{A}\ln(\frac{1}{1-Av}) - v]$$ Formula 9)

This can be expressed in Formula 10) by developing Formula 9) in Taylor series,

$$L = (\frac{1}{2\mu_o g} + \frac{Av}{3\mu_o g})v^2$$ Formula 10)

To change Formula 10) into Formula 11),

$$\frac{L}{v^2} = \frac{1}{2\mu_o g} + \frac{Av}{3\mu_o g}$$ Formula 11)

μ_o and constant *A* is determined from the gradient and intercept.

If the friction coefficient is exponential function like Formula 7), braking distance (L) can be developed as shown below.

$$L = \int \frac{v}{\mu_o g e^{-Bv}} dv = \frac{1}{B\mu_o g}[\frac{1}{B}(1-e^{Bv}) + ve^{Bv}]$$ Formula 12)

If it is assumed that bv is small in the Formula above, Formula 12) can be developed in Formula 13).

$$L = (\frac{1}{2\mu_o g} + \frac{Bv}{2\mu_o g})v^2$$ Formula 13)

From the gradient and intercept in Formula 14) which is changed from the Formula 13),

$$\frac{L}{v^2} = \frac{1}{2\mu_o g} + \frac{Bv}{2\mu_o g}$$ Formula 14)

μ_o and constant *B* are determined.

Friction coefficient measured with a traction trailer and braking distance measured using Sonata II are tabulated in Table 3) and 4). The tire used for this test is 195/65R14 and tests were performed on the wet Asphalt road surface with water depth of 1.5mm.

Table 3) Change of friction coefficient depending on speed change

	Tire 1			**Tire 2**			**Tire 3**			**Tire 4**		
Speed (KPH)	**40**	**60**	**80**	**40**	**60**	**80**	**40**	**60**	**80**	**40**	**60**	**80**
μ_p	**0.99**	**0.98**	**0.93**	**0.90**	**0.86**	**0.81**	**0.95**	**0.93**	**0.91**	**0.98**	**0.94**	**0.91**
μ_s	**0.69**	**0.63**	**0.54**	**0.58**	**0.52**	**0.45**	**0.71**	**0.62**	**0.53**	**0.76**	**0.66**	**0.58**
Braking distance (m)	**-**	**22.7**		**-**	**24.3**	**-**	**-**	**22.1**	**-**	**-**	**21.2**	**-**

Braking performances of tire 1, 2, 3 and 4 used are different from each other.

From the test result, it is observed that mp and ms decrease greatly as the speed increases during braking. and this means that friction coefficient is the function of speed.

Table 4) shows changes in braking distance depending on speed change.

Table 4) Change of braking distance depending on speed change

		Tire 1	Tire 2	Tire 3	Tire 4	Tire 5	Tire 6
Braking distance (m)	0 KPH	0	0	0	0	0	0
	50 KPH	16.9	17.2	17.1	17.6	18.3	17.2
	80 KPH	56.4	58.5	55.3	58.8	56.9	54.6

Intercept, gradient and μ_o value are calculated from L/v^2 and v plot of Formula 14) and recorded in Table 5).

Table 5) Intercept and gradient converted into model

	Tire 1	Tire 2	Tire 3	Tire 4	Tire 5	Tire 6
Intercept (xE-3)	3.310	3.136	3.868	3.506	4.670	4.101
Gradient (xE-5)	6.876	7.496	5.967	7.092	5.275	5.534
μ_o	1.189	1.255	1.020	1.223	0.843	0.960

The formula below is the function of speed for braking distance gained using this result.

$$L(m) = (0.00467 + 5.275 \times 10^{-5} \times v)v^2 \quad \text{Formula 15)}$$

In case of perfectly elastic body, the braking distance is in proportion to the squares of speed in general. However, the braking distance on the wet road surface becomes far longer than the theoretical value, which is proportional to the squares of the speed. The figure below compares the braking distance calculated in this paper with theoretical braking distance, which is proportional to the squares of speed.

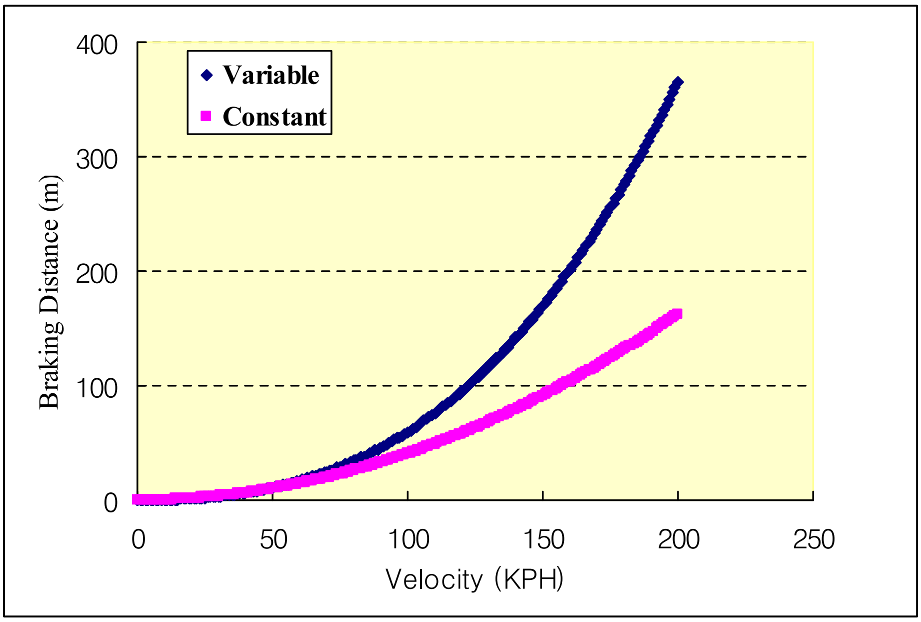

Figure 6) Comparison of theoretical braking distance depending on speed change and braking distance from the model formula

From the figure above, it is observed that the actual braking distance is much longer than the braking distance when the friction coefficient is constant irrespective of the speed. The reason is that a hydroplaning phenomenon occurs in high speed on the wet road surface. On the wet road surface, the tire drifts away from the road surface partially due to hydroplaning and this causes loss of grip.

5. Conclusion

For this research, braking distance depending on the speed is shown in the formula 15) using test results. The formula proposed in this research is almost identical to actual test results. However, the formula can be used in restricted conditions because the formula presented above calculated parameters using the test results under fixed conditions with the specific tire and specific road condition,.

Thus, under conditions with the fixed tire and road conditions, the braking distance depending on the speed of the car can be forecasted as a function of speed by measuring changes in friction coefficient and braking distance according to speed change. Furthermore, it seems possible to forecast the braking distance even if the car runs in high speed.